EARLY CRACKING OF CONCRETE PAVEMENT - CAUSES AND REPAIRS

By:
Gerald F. Voigt, PE
American Concrete Pavement Association
5420 Old Orchard Road, Suite A-100
Skokie, IL 60077

PRESENTED FOR THE 2002 FEDERAL AVIATION ADMINISTRATION AIRPORT TECHNOLOGY TRANSFER CONFERENCE

05/02

EARLY CRACKING OF CONCRETE PAVEMENT - CAUSES AND REPAIRS

Abstract

Concrete expands and contracts with variations in temperature. Concrete shrinks as it cures. Concrete slabs curl and warp from temperature and moisture gradients from the top to the bottom of the slab. These natural responses cause concrete pavement to crack at fairly regular intervals.

A fundamental of jointed concrete pavement design is to introduce a jointing system to control the location of this expected cracking. Of the three joint types, contraction, construction and isolation, contraction joints are specifically for crack control.

Statistically, contraction joint systems provide assurance of crack control in new concrete pavement. However, certain design or construction factors may influence the success of a contraction joint system. Substantial changes in the weather during and after construction can induce uncontrolled cracking despite proper jointing techniques. Because of the complexity of the interrelating factors, uncontrolled cracks will occur in some new concrete pavements. These cracks generally develop within the first sixty days.

When uncontrolled cracks do occur, agencies and contractors must address them to ensure long-term performance equivalent to normal pavement. There appears to be little consistency in this practice and this paper provides a summary of the causes and recommendations for minimizing the potential for cracking. The paper provides a single source review of the factors that contribute to uncontrolled cracking, including proper concrete mixture design and jointing techniques that can minimize risk of early uncontrolled cracking.

The paper concludes with a summary of industry standard practice for the repair of uncontrolled cracks.

Introduction

Like all materials, concrete expands and contracts with variations in temperature. Concrete shrinks as it cures. Concrete slabs curl and warp from temperature and moisture gradients from the top to the bottom of the slab. These natural responses cause concrete pavement to crack at fairly regular intervals.

A fundamental of jointed concrete pavement design is to introduce a jointing system to control the location of this expected cracking. Of the three joint types, contraction, construction and isolation, contraction joints are specifically for crack control.

Statistically, contraction joint systems provide assurance of crack control in new concrete pavement. However certain design or construction factors may influence the success of a contraction joint system. Substantial changes in the weather during and after construction can induce uncontrolled cracking despite normally proper jointing techniques. Because of the complexity of the interrelating factors, uncontrolled cracks will occur in some new concrete pavements. These cracks generally develop within the first sixty days.

When uncontrolled cracks do occur, agencies and contractors must address them to ensure long-term performance equivalent to normal pavement. There appears to be little consistency in this practice and this paper provides recommendations for repair of uncontrolled cracks. The remedial repairs outlined herein consider current practice using common techniques.

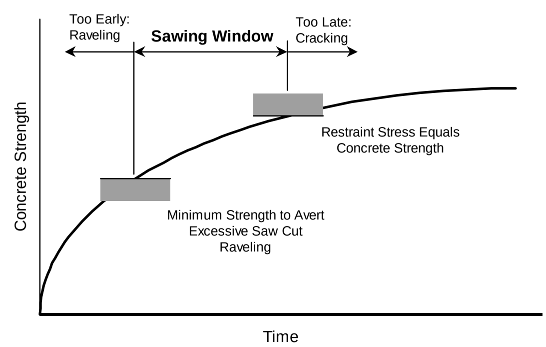


Figure 1. Sawing window (2).

Crack Control

Sawing the concrete with single-blade, walk-behind saws, makes contraction joints, either transverse or longitudinal. For wider paving, contractors may elect to use span-saws that are able to saw transverse joints across the full pavement width in one pass. A newer class of saw, the early-entry dry saw, is a walk-behind saw that allows sawing sooner than with conventional saws.

Concrete slabs crack when tensile stresses within the concrete overcome the tensile strength. At early ages, the tensile stresses develop from restraint of the concrete's volume change or restraint of slab bending from temperature and moisture gradients through the concrete.(1,2) Early volume changes are associated with the concrete's drying shrinkage and temperature contraction. Each transverse and longitudinal saw cut induces a point of weakness where a crack will initiate, and then propagate to the bottom of the slab.

In most cases, cracks first appear at large intervals, 10-45 m (30-150 ft), and then form at closer intervals over time. From this experience one may infer that restraint to volume change is the initial factor controlling cracking. Studies of plain pavements with 4-6 m (15-20 ft) transverse joint spacing support this inference.(1,3) These studies show that intermediate sawed joints — normally required to control cracking from shrinkage — sometimes do not crack for several weeks to months after opening the pavement to traffic. However, this may not be true on every pavement, and it may be very difficult to determine whether restraint to volume changes or restraint to gradients cause the first cracks.

Unfortunately, some concrete pavements do not crack at the saw cuts but instead they crack at unplanned locations. The common terms for these early cracks are uncontrolled cracks or random cracks.(2,4) There are many reasons that uncontrolled cracks occur, and it is usually a challenging task to isolate the cause(s). However, experience in examining projects has led to identification of some consistent characteristics.

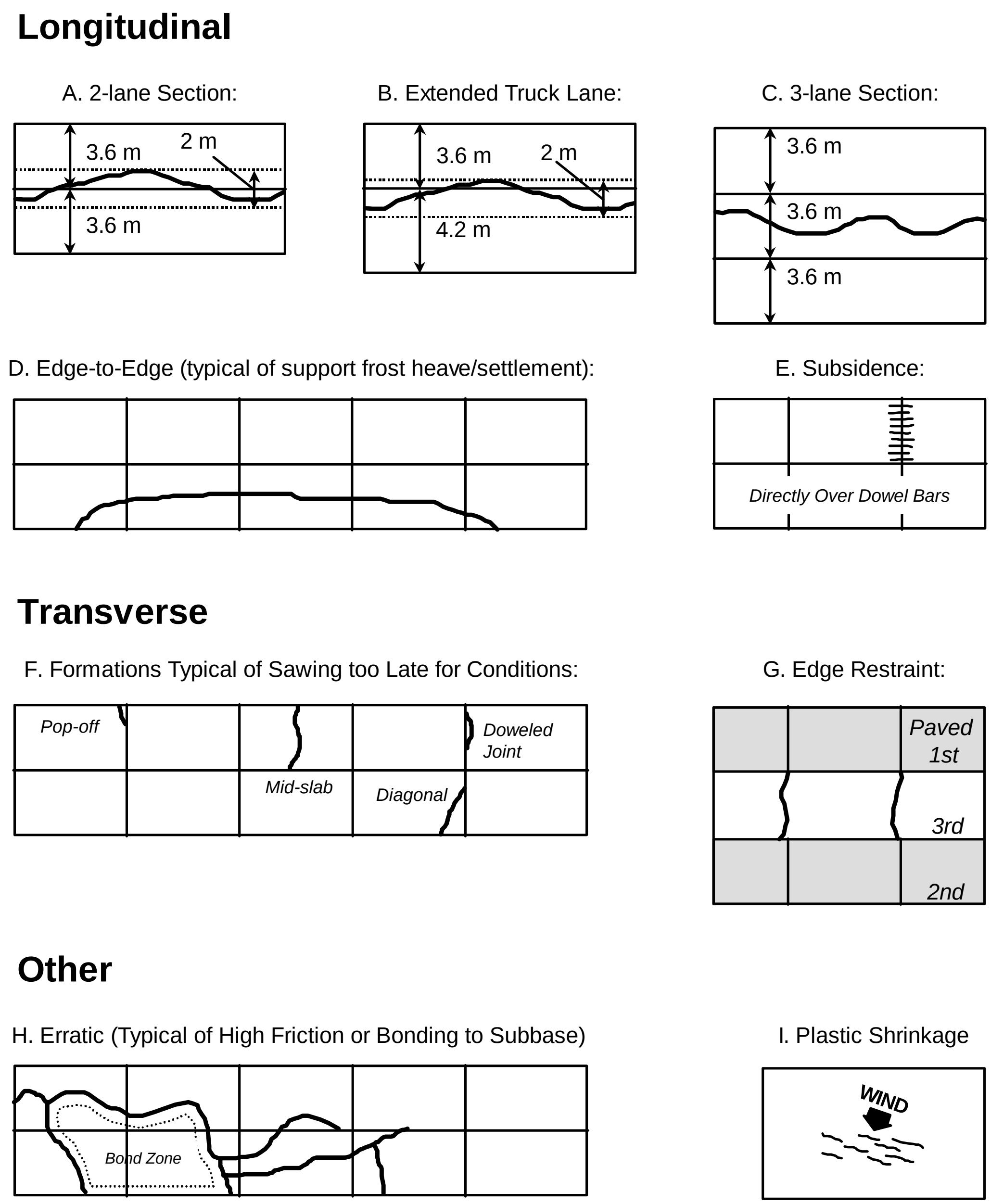
Timing of Sawing Joints — There is an optimum time to saw contraction joints in new concrete pavements. That time occurs within the sawing window (Figure 1).(2,5) The window is a short period after placement when the concrete pavement can be cut and successfully control crack formation. The window begins when concrete strength is acceptable for sawing without excessive raveling along the cut. Sawing too early causes the saw blade to break aggregate particles free from the pavement surfaces along the cut. The jagged, rough edges are termed raveling. Some raveling is acceptable if the dimension saw cut made for a joint sealant would remove the ravel edge. If the raveling is too severe, it will affect the appearance and ability to seal the joint.

The window ends when the concrete's volume reduces significantly (from drying shrinkage or temperature contraction) and restraint of the reduction induces tensile stress greater than the tensile strength. Certain design features or weather conditions can considerably shorten the window. Under most weather conditions and for typical pavement designs, the window will be long enough to complete sawing with excellent results. In extreme conditions, the window can be so short as to be impracticable for crack control.

Formation of Uncontrolled Cracks — The formation or orientation of uncontrolled cracks can indicate the possible causes. If a crack reverses direction, or develops in an unusual orientation, it may have been influenced by high friction or bonding between the concrete slab and subbase.(2) When an uncontrolled crack extends across the entire width of a paving slab, or begins and ends at a functioning joint, the possibility of late sawing exists. In most cases, uncontrolled longitudinal cracks from late sawing will be in predictable locations as depicted in Figure 2(A-C). Transverse cracks from late sawing are less predictable, but generally extend across the entire slab or traverse diagonally as shown in Figure 2(F-G).

Examining the faces from a core taken through an uncontrolled crack provides a clue to the time the crack occurred. Cracks that form after some reasonable strength development will break through some coarse aggregate particles. Cracks that travel around the coarse aggregate particles likely formed at a very early age, before the cement paste was able to bond sufficiently to the aggregates. This information may help identify contributing factors to uncontrolled cracking.

Figure 2. Typical crack formations.



Restraint of shrinkage or temperature contraction by high subbase friction or slab edge contact generally causes cracks to form early in the concrete hydration period. When a subbase contracts from a reduction in temperature, it may induce reflective cracks in the overlying concrete at an early age. The bond strength between the cement paste and dirty, dusty or extremely hard coarse aggregate also may be low at an early age, which could also contribute to cracking around coarse particles.

Cracks that Occur While Sawing — At or near the end of the sawing window, cracks may form while the saw operator is making a cut. These cracks often occur as the saw progresses to

Table 1. Joint sawing depth recommendations for conventional saws.

	TRANSVERSE[1]	LONGITUDINAL
Granular Subbases (low friction)	D/4	D/3
Stabilized[2] Subbases (high friction)	D/3	D/3

1. Early-entry dry saws that permit early sawing do not require these sawing depths.
2. Stabilized subbases include the following: asphalt-treated, cement-treated, econocrete, lean concrete, asphalt-treated open graded and cement-treated open graded.

within about 1 m (3 ft) of the free edge of the slab as shown in Figure 2(F). Pop-off cracks are an indication that sawing is too late for the prevailing conditions. There is a higher tendency for pop-off cracks if a high wind is blowing against the edge of the slab, accelerating evaporation and shrinkage. Experienced saw operators will orient the direction of sawing with the wind whenever possible.

Cracks that Occur Well After Sawing — Sometimes cracks continue to form as much as 60 days to 2 years after paving and sawing are complete. In some cases these may be cracks that formed early but were not visible. In other cases, uncontrolled cracking that first occurs or continues to develop well after paving and sawing is a clue that something is restraining or moving the concrete slabs to cause high tensile stresses. This situation may be the result of grade settlement or frost heave. Cracks from grade problems will typically begin and end at the pavement edges (Figure 2D).

Saw Cut Depth

The influence of the saw cut depth on early cracking primarily depends upon the time of sawing. According to one study(3), early-age sawing methods with sawing depths less than 0.25d (d=slab depth), should provide better crack control than conventional methods with depths of 0.25d or 0.33d. The study found that sawing sooner with early-age saws can take advantage of larger changes in the concrete's surface moisture content or surface temperature, which has been shown to induce cracking.(2) The study also verified the effectiveness of early-age sawing methods with field experience on 330 mm (13 in.) plain concrete pavement, made with a variety of coarse aggregates, on granular soils. Further verification is necessary for early age crack control in plain concrete on stabilized subbases that induce more restraint and for longitudinal joints in pavements more than 150 mm (6.0 in) thick.

While it is not precisely proven that saw cut depth alone directly relates to occurrence of transverse or longitudinal cracking, it is a commonly specified factor. Table 1. is a summary of recommended saw cut depths.

Deeper saw cuts are necessary for conventional sawing equipment because the concrete is generally under more restraint than when sawed with early-age sawing equipment. Practical experience shows that transverse cuts from one-fourth to one-third the slab thickness (0.25d to 0.33d) will provide crack control under most circumstances for conventional sawing operations. However, there is little information to quantify the increased probability of uncontrolled cracking should the cut depths not meet a specified (0.25d or 0.33d) minimum depth. One joint sawing study[2] attempted to determine the necessary transverse cut depth for conventional sawing equipment. It concluded that there are too many confounding factors to develop a verified recommendation for transverse joints.

For longitudinal contraction joints, uniformity in concrete strength, slab thickness and cut depth improves the probability of crack control. According to a Texas study[6], a saw depth of 0.25d controls longitudinal cracking with 98% reliability in mixtures containing crushed limestone aggregate, and with 86% reliability in mixtures containing river gravel. However, other experiences show that more factors also may be involved in longitudinal cracking. On one test pavement in Minnesota, sections on granular subbase had very little longitudinal cracking, while sections on asphalt or cement stabilized materials — that induce higher frictional restraint — had extensive uncontrolled longitudinal cracking.[2] This occurred even though the contractor formed the longitudinal joint at a similar time and orientation during paving.

Shallow Saw Cuts — On projects where contractors use conventional diamond-bladed sawing equipment, shallow (less than 0.25d or 0.33d) saw cuts are often a symptom of late sawing rather than a direct cause of cracking through poor equipment set-up. When cracking is imminent near the end of the sawing window, saw operators may tend to push a saw too fast, causing the saw blade to ride up out of its full cut. Another possible cause of shallow saw cuts are worn abrasive saw blades. During use, the diameter of an abrasive blade becomes progressively smaller as the abrasive cutting material wears away. Saw operators must closely monitor abrasive blade wear and replace worn blades to consistently meet depth requirements.

Weather & Ambient Conditions

The weather almost always has a role in the occurrence of uncontrolled cracking. Air temperature, wind, relative humidity, and sunlight all influence concrete hydration and shrinkage. These factors may heat or cool concrete or draw moisture from exposed concrete surfaces. The subbase can be a heat sink that draws energy from the concrete in cold weather, or a heat source that adds heat to the bottom of the slab during hot, sunny weather.

Under warm, sunny summer conditions, the maximum concrete temperature will vary depending upon the time of day when the concrete is paved. Concrete paved in early morning will often reach higher maximum temperatures than concrete paved during the late morning or afternoon because it receives more radiant heat. As a result, concrete paved during the morning will generally have a shorter sawing window, and often will exhibit more instances of uncontrolled cracking.

After the concrete sets, uncontrolled cracking might occur when ambient conditions induce differential thermal contraction.[2,7] Differential contraction is a result of temperature differences throughout the pavement depth. Research indicates that a sudden drop in surface temperature more than 9.5°C (15°F) can result in cracking from excessive surface contraction.[2] This degree of temperature change is common year-round in arid climates, and possible in most other climates during the spring and fall when air temperatures drop significantly from day to night. Differential contraction also may occur when a rain shower cools the slab surface, or when the surface cools after removing insulating blankets from fast-track concrete.

Subbase Conditions

Stabilized subbases[1] may induce uncontrolled cracking because of the high friction and, in some cases bonding, between the subbase and concrete slab. The friction or bond restrains the concrete's volume change (shrinkage or temperature contraction), inducing higher tensile stresses than might occur in concrete pavement on a granular subbase with a low coefficient of friction. As a result, cracks tend to form at a closer interval and sooner than might be expected in new pavement on a granular subbase.

Figure 3. Cores removed from cracked pavement showing bond between surface and subbase.

One study[(2)] found that cracking will occur from smaller drops in surface temperature as subbase friction increases. This relationship implies that high friction subbase materials have a smaller sawing window than low friction subbase materials. If the frictional restraint is so great as to create a bond between the subbase and overlying concrete, there may be little chance of controlling cracking.

There have been well-documented occurrences of erratic uncontrolled cracking on projects with econocrete, cement-treated, asphalt-treated, and permeable asphalt treated subbases that were known to have bonded to the concrete pavement.[(8-10)] Cores examined from these projects typically revealed that the cracks traveled around coarse aggregate particles, indicating very early formation. The cores also showed significant bonding between the subbase and concrete pavement layers. (Figure 3). Cracks from bonding to the subbase may initiate from the bottom of the slab sometimes reflecting from shrinkage cracks in the stabilized subbase. Cracks from subbase bond/friction are erratic in orientation, sometimes reverse direction and seem to follow zones of varying restraint between the concrete and subbase (Figure 2H).

In addition to adding restraint, bonding or high friction between the pavement and subbase will reduce the effective saw cut depth. For example, a typical 250-mm (10-in.) slab requires a 63-mm (2.5-in) saw cut to meet typical 0.25d requirements. If the slab bonds to a 100-mm (4-in.) stabilized subbase, the effective depth of the saw cut is only about 0.18d, which is usually not adequate to control cracking with normal sawing equipment and timing.

The potential for bonding between the concrete and subbase can be minimized with the application of a bond-breaking medium. For lean concrete or econocrete subbases, current practice includes two heavy spray applications of wax-based curing compound on the subbase surface.[(2,11)] There are no common bond-breaker recommendations for cement-treated subbases or asphalt-stabilized subbase materials. However, many cement-treated subbase specifications recommend liquid asphalt for curing, which also may serve as a bond-breaker or reducer.

---

[1] Stabilized subbases include the following: asphalt-treated, cement-treated, econocrete, lean concrete, asphalt-treated open graded and cement-treated open graded.

In some cases trimming prior to paving disturbs the subbase surface. After trimming, the surface may be rough in certain locations creating an excellent surface for bonding to occur. One of the following methods will minimize bonding in trimmed areas:

- Reapplication of cutback asphalt curing agent and spread of thin layer of sand before paving.
- An application of two coats of wax-based curing compound before paving.

Slag aggregate or very dry granular subbases also may contribute to uncontrolled cracking. Some contractors postulate that the dry subbase draws moisture from the concrete pavement, which dries the lower portion of the slab before the middle or the top. This induces differential shrinkage similar to surface drying from high winds. Most specifications for granular materials appropriately require moistening a dry granular subbase surface before placing any concrete. Moistening efforts are very important with slag subbase materials due to the high absorptive capacity of the aggregates.

Concrete Mixture

Regardless of the ambient conditions, subbase friction or other related factors, the concrete mixture itself is a primary factor in defining the potential for uncontrolled cracking. Three mixture factors influence this potential:

- Portland cement and/or mineral admixture content
- Fineness of the sand (fine aggregate)
- Type of coarse aggregate (size or quantity)

The first two factors influence the water required in the mixture for workability. Total water content is directly related to volume shrinkage. Consequently, the potential for uncontrolled cracking is directly related to water demand. The coarse aggregate influences the temperature sensitivity of the concrete. Concrete that is more temperature sensitive will expand or contract more with temperature change, increasing cracking potential.

Portland Cement — The strength of concrete is directly influenced by the quantity of cement and the water cement ratio. Increasing the quantity of cement and lowering the water cement ratio generally helps produce a denser and more durable mixture with higher early strength, but it may also contribute to a higher potential for uncontrolled cracking. Mixtures with higher quantities of portland cement require more mixing water and consequently shrink more. Even if the water to cementitious materials ratio is minimized, the actual volume of water increases with higher cementitious material content.

Conversely, mixtures containing certain fly ashes, ground-granulated blast furnace slag (GGBFS) or lower quantities of portland cement can delay early age strength development in cooler weather. Depending upon the air, subbase and concrete temperature, this could delay concrete setting and the ability to saw without excessive raveling. After setting, the time available for sawing before the onset of cracking is usually much shorter than normal. This increases the risk of uncontrolled cracking in cooler weather. Many agencies specify a usage period for such mixtures, which prohibit their use in early spring or late fall.

Sand — It is normal to see pavement specifications that requires the sand to meet the minimums of ASTM C-33.(12) ASTM C-33 provides upper and lower limits for percentage of material passing/retained on sieves from 3/8 in. to No. 100 (9.5 to 0.15 mm). When applied indiscriminately, ASTM C-33 requirements may increase potential for uncontrolled cracking of pavement concrete.

Generally, concrete with a high cement factor should include coarse sand. ASTM C-33, Paragraph 6.2 allows reduction of the portion of sand passing the 300 µm and 150µm (No. 50 and No. 100) sieves to 5 and 0 percent, respectively for:

- Pavement grade concrete (more than 3% entrained air).
- Air entrained concrete with more than about 134 kg (400 lb) of cement per cubic meter (yard).
- Non air-entrained concrete with more than about 134 kg (400 lb) of cement per cubic meter (yard).

However, in practice this clause is often ignored or the specifier is not inclined to follow the recommendation.

While ASTM C-33 covers the fine sand issue, its upper grading limits are more suitable for masonry mixtures. Some state specifications allow similarly fine sands. The minus 300 µm (No. 50) sieve portion of these sands directly influences the water demand and therefore influences the potential for uncontrolled cracking when used in pavement.

Figure 4a represents a sand gradation that increases the potential for uncontrolled cracking, and in fact was used on an actual project that exhibited uncontrolled cracking. The material does not meet the grading requirements of ASTM C-33, but is acceptable under some state

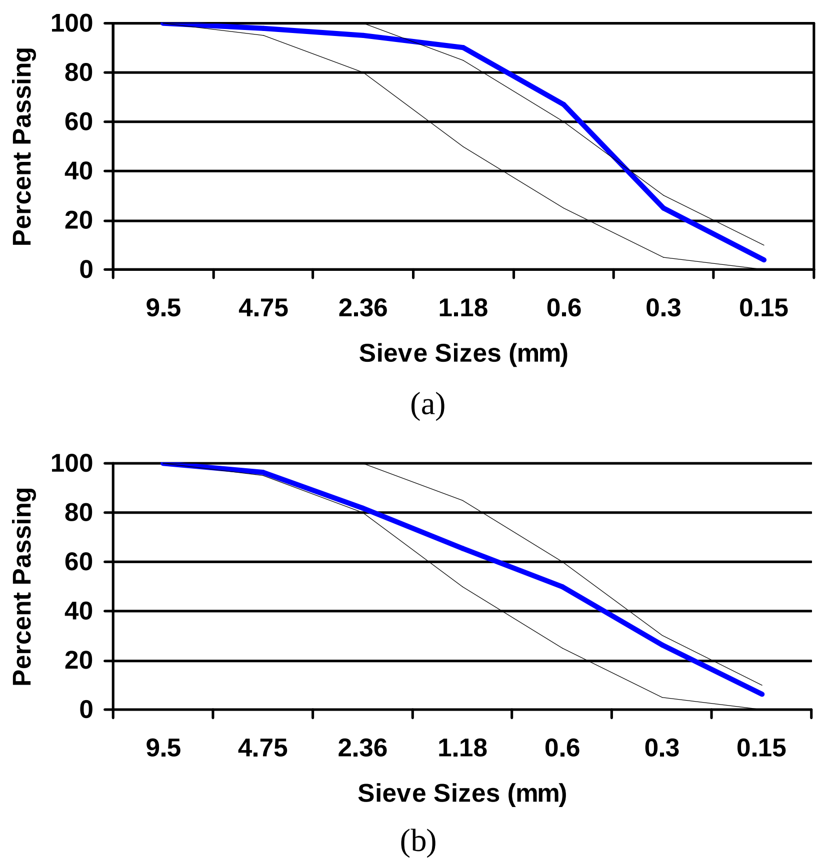


Figure 4. (a) Grading distribution of sand that does not meet ASTM C-33 limits and results in a mixture prone to uncontrolled cracking. (b) Grading distribution of sand that meets ASTM C-33 limits with high bulking volume that results in a mixture prone to uncontrolled cracking.

specifications. The extra fine sand requires a high water volume, which increases its bulking volume.

The sand in Figure 4b also has a high potential for uncontrolled cracking even though it meets the grading limits of ASTM C-33. This sand has a high bulking volume reflected by nearly 60 percent passing the 1.18 mm (No. 16) sieve.

The bulking factor for fine sand is more than twice that of coarse sand.(13) Bulking is an increase in volume as compared to dry sand (Figure 5). Bulking volume directly influences bulk shrinkage and the moisture requirements for mobilizing the sand portion of the concrete mixture.

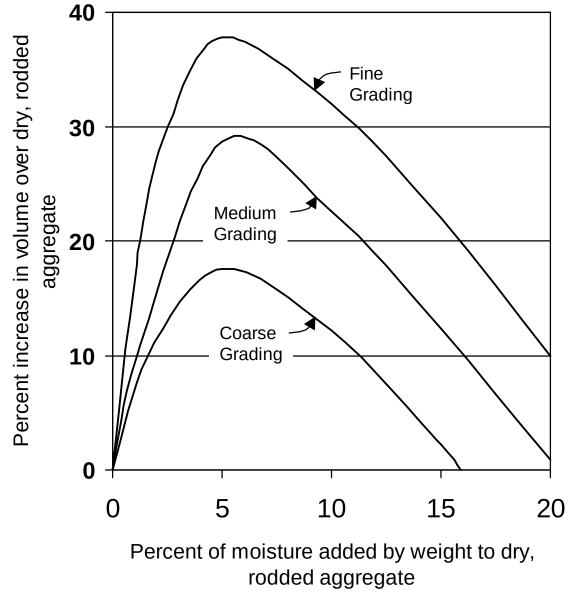


Figure 5. Bulking Volume Increase for Surface Moisture on Graded Sands

It is not uncommon for sands to meet the grading requirements of ASTM C-33 and lack the characteristics that are desired for use in pavement concrete. Paragraph 6.3 of ASTM C-33 stipulates the following acceptability characteristics:

- No more than 45% of material is retained on any one sieve.
- Fineness Modulus (FM) from 2.3 to 3.1.

The sand gradation plotted in Figure 4b is acceptable according to the ASTM C-33, except that more than 50% of the sand is smaller than the 600 μm (No. 30) sieve size. Concrete made with this sand will likely exhibit a high bulking volume, which will increase water required to mobilize the fine material and consequently the potential for uncontrolled cracking.

The sand gradation plotted in Figure 6 is considered acceptable for use in pavement with no concern for excessive shrinkage.

ASTM C-33's Fineness Modulus limit of 3.1 is too low for sands ideal for pavement concrete. A Fineness Modulus of up to 3.8 can provide excellent results for pavement. In fact,

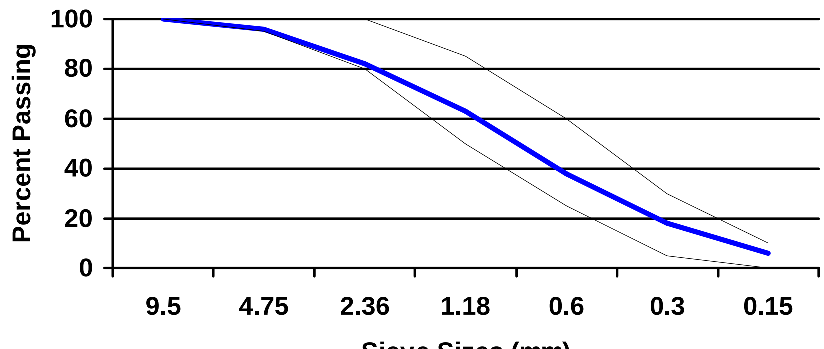


Figure 6. Grading distribution of well-graded sand with little potential to contribute to uncontrolled cracking.

sand that meets ASTM C-33's lower gradation limit will have a Fineness Modulus of 3.45. However, sand with a well-graded character and a FM above 3.1 may not be available through local suppliers. If so, it may be necessary to use manufactured sands to obtain the desirable characteristics.

Coarse Aggregate — The coarse aggregate type will influence the amount of temperature expansion or contraction of concrete. Concrete that is more temperature sensitive has an increased potential for uncontrolled cracking. Limestone, granite and basalt have lower coefficients of thermal expansion than quartz, sandstones or siliceous gravels. These differences should be considered in design with a shorter spacing between contraction joints applied to concrete that is more temperature sensitive. The time of cracking may also be earlier for more temperature sensitive concrete. Field tests show that cracks form at the saw cut sooner and more frequently with concrete made from river gravel than concrete made with crushed limestone.(6)

Combined Aggregates — By examining the combined aggregate one can predict the nature of the concrete. Shilstone(14) and others(15) have provided a useful evaluation technique for predicting the constructability of concrete mixtures. While this technique cannot cover every possible combination, it can provide some insight into the response of most concrete mixtures. A clear benefit is that the technique identifies concrete mixtures that finish poorly or may segregate under vibration.

Curing Conditions

The internal temperature and moisture of concrete will also influence the time available for joint sawing. The temperature relates to the concrete's strength gain and (in part) controls the ability to start sawing and to finish sawing before the onset of cracking. The simplest way to determine the end of the sawing window is to monitor the concrete surface temperature.(2) It is preferable to complete sawing before the concrete pavement surface temperature begins to fall since thermal contraction begins as soon as the concrete temperature falls.

Higher concrete tensile strength should enable the concrete to withstand more tensile stress when it first cools and undergoes temperature differentials. However, concrete mixtures that gain strength rapidly may actually have a shorter window for sawing than normal mixtures if the heat from hydration is high. In certain weather or ambient conditions, these mixtures may experience a larger surface temperature drop than mixtures that gain strength more slowly and do not become as warm. It is not uncommon for concrete pavement surface temperatures to exceed 45 °C (113 °F) in summertime, particularly for fast-track concrete paving.(5,7)

Contractors should become familiar with the heat development potential of job mixtures. Concrete maturity testing is a valuable tool for this purpose. By monitoring the surface temperature a contractor will know the approximate concrete strength and also the point when surface temperature begins to decline and sawing should be completed.

Joint Spacing

Theoretical and practical studies of un-reinforced concrete pavement have determined that the optimal spacing between joints depends upon slab thickness, concrete aggregate, subbase, and climate.[(1)]

Equation 1 is an empirical formula related to minimizing uncontrolled cracking. Equation 1 approximates a slab length to radius of relative stiffness ratio of seven.[2] Equation 1 may be used to determine the maximum recommended joint spacing based on slab thickness and subbase type. Slabs kept to dimensions shorter than those determined by the equation will have minimal risk of uncontrolled cracking.

$$ML = T \times C_S \qquad \text{(Eq. 1)}$$

where:

ML = Maximum length between joints (See Notes 1 and 2)
T = Slab thickness (Either metric or English units)
C_S = Support constant
Use 24; for subgrades or granular subbases.
Use 21; for stabilized sub-bases (cement or asphalt)

Notes:

1. *The spacing of transverse joints in plain (un-reinforced) concrete pavement should not exceed 6 m (20 ft) for slabs greater than 250 mm (10 in.) thick.*
2. *A general rule-of-thumb requires that the transverse joint spacing should not exceed 125% of the longitudinal joint spacing.*

The climate and coarse aggregate common to some geographic regions may allow transverse joints to be further apart, or require them to be closer together than Equation 1 determines. It is advisable to check the transverse and longitudinal contraction joint spacing to see if it is within the limits recommended for different coarse aggregates (see Section Coarse Aggregate). However, unless experience with local conditions and concrete aggregates indicates otherwise, use Equation 1 to determine the maximum allowable transverse joint spacing for un-reinforced pavements.

A transverse joint spacing up to 9 m (30 ft) is allowable for pavements reinforced with distributed steel reinforcement. The purpose of distributed steel is to hold together any intermediate (mid-panel) cracks that will develop in the long panels between transverse joints[3].

---

[2] Theoretical research suggests that an even closer joint spacing may be desirable than is computed by Eq 1 for stabilized subbases. These studies suggest that transverse joints should not exceed a spacing that maintains the ratio of the slab length (L) to the radius of relative stiffness (l) below five. (16,17) However, the occurrence of early cracking has been related to a maximum (L/l) ratio of seven as related in Eq. 1. It is impracticable to determine an (L/l) ratio in the design phase because specific job materials are unknown at that time. Therefore Eq. 1. provides a linear relationship that is simpler to apply.

[3] Pavements with distributed steel are often called jointed reinforced concrete pavements (JRCP). In JRCP, the joint spacing is purposely increased and reinforcing steel is used to hold together intermediate cracks. If there is enough distributed steel within the pavement (0.10 to 0.25% per cross-sectional area), the mid-panel cracks do not detract from the pavement's performance.[(19)] However, if there is not enough steel, the steel can corrode or rupture and the cracks can start to open and deteriorate.

Saw Blade Selection

Raveling usually occurs when sawing too soon, but the saw equipment can also cause it.[18] A saw blade must be compatible with the power output of the saw, the concrete mixture, and the application. An improper saw blade will dull rapidly and can dislodge aggregate while trying to cut. In some cases, switching to a different saw blade results in correction of the problem.

Plugging or clogging of the cooling water tubes on a diamond-bladed saw also may cause a raveled cut. Therefore it is important for saw operators to monitor the sawing equipment to determine if it is creating a raveled cut in concrete that is otherwise ready for sawing.

Experienced saw operators rely on their judgment and the scratch test to make this determination, and then adjust their equipment so that it can operate correctly. The scratch test is the most common and one of the simplest tests that contractors use to determine when to begin sawing.[18] The test requires scratching the concrete surface with a nail or knife blade, and then examining how deep the surface scratches. As the surface hardness increases the scratch depth decreases. In general, if the scratch removes the surface texture it is probably too early to saw without raveling problems.

Misaligned Dowels

Neither dowel bar alignment nor the mere presence of dowel bars will alter the formation of initial cracking. The alignment of dowel bars only becomes a factor of restraint when the following conditions exist:

- A crack extends below the joint saw cut, indicating that joint is working.
- Misalignment exceeds a tolerance of 3% or more.

If there is no crack meeting the joint saw cut then the dowels do not hinder concrete temperature contraction and cannot influence the development of an uncontrolled crack elsewhere in the slab (Figure 7).

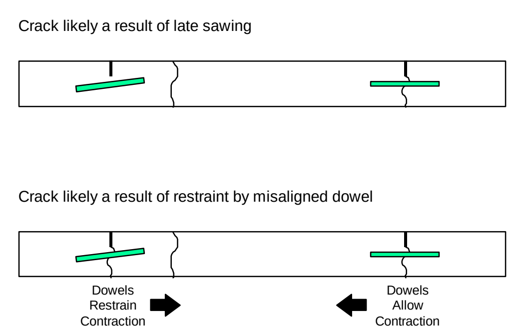


Figure 7. Condition for cracks to form from misaligned dowels.

If a crack exists below the saw cut, and an uncontrolled crack occurs nearby, then it is possible that the dowels are misaligned or not sufficiently lubricated to allow joint opening or closing. Cracks from this situation typically occur along the ends of the embedded dowel bars.

Rapid Surface Moisture Evaporation

It is important not to confuse cracks from restraint of the concrete at early ages, to plastic shrinkage cracks. Plastic shrinkage cracks are generally tight, about 0.3-0.6 m (1-2 ft) long, extend down about 25-100 mm (1-4 in.) from the surface, and form in parallel groups perpendicular to the direction of the wind at the time of paving. Plastic shrinkage cracking is a result of rapid drying at the concrete pavement surface, and therefore adequate curing measures are necessary to prevent their occurrence.[5] Experience has shown that these cracks rarely influence the long term performance of a pavement.

Job Site Adjustments

Adjustments to the sawing operations must be made whenever uncontrolled cracks occur during or before sawing. Four possible alternatives exist:

- Omit the saw cut if a crack forms at or near the planned location for a joint before sawing starts.
- Stop sawing the joint upon noticing a pop-off crack (to prevent creation of a potential spall between the saw cut and the crack).
- Saw every third or fourth joint if uncontrolled cracking is imminent (for example, in the event of unexpected weather changes, like storms or cold fronts).
- Switch to early-entry saws in the event that extreme conditions make it impractical to prevent uncontrolled cracking with conventional saws.

When skipping saw cuts to prevent cracking, the initial contraction joints may open much wider then the 2 or 3 joints sawed at a later time. However, this is a relatively minor problem to accept in order to provide an additional method to avoid uncontrolled cracking.

Recommended Repairs

Table 2 (next page) outlines recommended repairs for uncontrolled cracking and spalling along saw cuts.

Conclusions

1. The ability to adequately saw concrete pavement without excessive raveling and before uncontrolled cracking, depends upon design features, concrete mixture materials, jointing techniques and environmental circumstances.

2. Minimizing the potential for uncontrolled cracking will only become a reality when the design and the construction team each look purposely at material selections with the intent to improve constructability.

3. For clarity, agencies should develop jointing specifications that incorporate the sawing window concept, recognizing the possibility of raveling and uncontrolled cracking.

4. It is important that jointing specifications provide reasonable guidance to the contractor and inspector for handling uncontrolled cracking that may occur before or while sawing, including skipping joints and using early-age saws.

5. Agencies should consider adding a damage repair clause to their specification, or modifying the existing clause to conform with the thorough methodology outlined in Table 2.

Table 2. Recommended Repairs of Cracking in Concrete Pavement Construction.

Defect	Orientation	Location[a]	Description	Recommended Repair	Alternate Repair
Plastic Shrinkage	Any	Anywhere	Only partially penetrates depth	Do nothing	Fill with HMWM[b]
Uncontrolled Crack	Transverse	Crosses or ends at transverse joint	Full-depth	Saw & seal the crack; Epoxy uncracked joint saw cut	
Uncontrolled Crack	Transverse	Relatively parallel & w/in 4.5 ft of joint	Full-depth	Saw & seal the crack; Seal joint	FDR[d] to replace crack and joint
Saw cut or Uncontrolled Crack	Transverse	Anywhere	Spalled	Repair spall by PDR[e] if crack not removed	
Uncontrolled Crack	Longitudinal	Relatively parallel & w/in 1 ft. of joint; May cross or end at longitudinal joint	Full-depth	Saw & seal the crack; Epoxy uncracked joint saw cut	Cross-stitch[f] or Slot-stitch crack
Uncontrolled Crack	Longitudinal	Relatively parallel & in wheel path (1-4.5 ft from joint)	Full-depth, hairline or spalled	Remove & replace panel (slab)	Cross-stitch[f] or Slot-stitch crack
Uncontrolled Crack	Longitudinal	Relatively parallel & further than 4.5 ft from a long. joint or edge	Full-depth	Cross-stitch[f] or Slot-stitch crack; Seal long. joint	
Saw cut or Uncontrolled Crack	Longitudinal	Anywhere	Spalled	Repair spall by PDR[e] if crack not removed	
Uncontrolled Crack	Diagonal	Anywhere	Full-depth	FDR[d]	
Uncontrolled Crack	Multiple per panel (slab)	Anywhere	Two full depth cracks dividing panel (slab) into 3 or more pieces	Remove & replace panel (slab)	

[a] 1 ft = 0.3048 m
[b] HMWM = High molecular weight methacrylate poured over surface and sprinkled with sand for skid resistance.
[d] FDR = full-depth repair; 10 ft long by one lane wide. Extend to nearest transverse contraction joint if 10-ft repair would leave a segment of pavement less than 10 ft long (see ACPA publication TB002P).
[e] PDR = partial-depth repair; Saw around spall leaving 2 in. between spall and 2-in. deep perimeter saw cuts. Chip concrete free, then clean and apply bond breaker to patch area. Place a separating medium along any abutting joint or crack. Fill area with patching mixture. (see ACPA publication TB003P)
[f] Cross-stitching; for longitudinal cracks only, drill holes at angle, alternating from each side of joint on 30-36 in. spacing. Epoxy deformed steel tiebars into holes.
[g] Slot-stitching; for longitudinal cracks only; Deformed bars grouted into slots sawed across the crack; Backfill with non-shrink, cement-based mortar.

References

1. Design and Construction of Joints for Concrete Highways. TB010P. American Concrete Pavement Association, Arlington Heights, IL, 1991.

2. Okamoto, P., etal. Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements, Volume 1: Final Report. FHWA-RD-91-079. FHWA, U.S. Department of Transportation, February 1994.

3. Zollinger, D., etal. Sawcut Depth Considerations for Jointed Concrete Pavement Based on Fracture Mechanics Analysis. In Transportation Research Record 1449, TRB, National Research Council, Washington, D.C., 1994, pp. 91-100.

4. Joint and Crack Sealing and Repair for Concrete Pavements. TB012P. American Concrete Pavement Association, Arlington Heights, IL, 1993.

5. Fast-Track Concrete Pavements. TB004.02P. American Concrete Pavement Association, Skokie, IL, 1994.

6. Saraf, C.L., and B.F. McCollough. Controlling Longitudinal Cracking in Concrete Pavements. In Transportation Research Record 1043, TRB, National Research Council, Washington, D.C., 1985, pp. 8-13.

7. Accelerated Rigid Paving Techniques: State-of-the-Art Report (Special Project 201). FHWA-SA-94-080. FHWA, U.S. Department of Transportation, December 1994.

8. Halm, H.J., W.A. Yrjanson and E.C. Lokken. Investigation of Pavement Cracking Utah I-70, Phase I Final Report. ID-70-1 (31) 7. American Concrete Pavement Association, Arlington Heights, IL, 1985.

9. Voigt, G.F., Cracking on Highway 115 Petersborough, Ontario. American Concrete Pavement Association, Arlington Heights, IL, 1992.

10. Voigt, G.F., Investigation of Pavement Cracking on General Aviation Airport, Fremont Nebraska. American Concrete Pavement Association, Arlington Heights, IL, 1994.

11. Subbases and Subgrades for Concrete Pavements. TB011P. American Concrete Pavement Association, Skokie, IL, 1991.

12. Standard Specification for Concrete Aggregate, ASTM C-33, American Society of Testing Materials, Philadelphia, PA.

13. Kosmatka, S.H., Panarese, W.C., "Design and Control of Concrete Mixtures," 13th Edition, EB001.13T, Portland Cement Association, Skokie, IL, 1990.

14. Shilstone, J.M., "Concrete Mixture Optimization," Concrete International, American Concrete Institute, Detroit, MI, June 1990, pp.33-39.

15. Lafrenz, J., " Aggregate Gradation Control for PCC Pavements," International Center for Aggregates Research, 5th Annual Symposium, University of Texas, Austin, TX, April 21-23, 1997.

16. Rasmussen, R.O., and D.G. Zollinger, The Development of a Mechanistic-Empirical Design Model for Uncontrolled Cracking in Jointed Plain Concrete Pavements using the LTPP GPS-3 Data, Paper Prepared for Presentation, 76th Annual Meeting, Transportation Research Board, Washington, D.C., 1997.

17. Ioannides, A.M., Salsilli-Murua, R., Temperature Curling in Rigid Pavements: An Application of Dimensional Analysis. In Transportation Research Record 1227, TRB, National Research Council, Washington, D.C., 1990, pp. 1-11.

18. Construction of Portland Cement Concrete Pavements, Participant's Manual. FHWA-HI-96-027, National Highway Institute, FHWA, U.S. Department of Transportation, March 1996.

19. Smith, K.D., etal, "Performance of Concrete Pavements, Evaluation of In-Service Concrete Pavements," *Volume 1 - Final Report*, DTFH-61-91-C-00053, Federal Highway Administration, Washington, DC, April 1995.

20. Guide Specifications for Highway Construction 1993. American Association of State Highway and Transportation Officials, Washington, D.C., 1993, pp. 139-163.